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Reconstructing a String-Inspired Non-minimally Coupled Quintom Model *

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Abstract

Motivated by the recent work of Zhang and Chen [1], we generalize their work to the non-minimally coupled case. We consider a quintom model of dark energy with a single scalar field T given by a Lagrangian which inspired by tachyonic Lagrangian in string theory. We consider non-minimal coupling of tachyon field to the scalar curvature, then we reconstruct this model in the light of three forms of parametrization for dynamical dark energy.

*__Dedicated to the 60 year Jubilee of Professor Reza Mansouri__

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1 Introduction

Nowadays it is plainly believed that the universe is experiencing an accelerated expansion. Recent observations from type Ia supernovae [2] in associated with Large Scale Structure [3] and Cosmic Microwave Background anisotropies [4] have provided main evidence for this cosmic acceleration. In order to explain why the cosmic acceleration happens, many theories have been proposed. Although theories of trying to modify Einstein equations constitute a big part of these attempts, the mainstream explanation for this problem, however, is known as theories of dark energy.

The combined analysis of cosmological observations suggests that the universe consists of about 70% dark energy, 30% dust matter (cold dark matter plus baryons), and negligible radiation. Although the nature and origin of dark energy are unknown, we still can propose some candidates to describe it, namely since we do not know where this dark energy comes from, and how to compute it from the first principles, we search for phenomenological models. The astronomical observations will then select one of these models. The most obvious theoretical candidate of dark energy is the cosmological constant λ (or vacuum energy) [5, 6] which has the equation of state parameter $w = -1$. However, as it is well known, there are two difficulties that arise from the cosmological constant scenario, namely the two famous cosmological constant problems — the "fine-tuning" problem and the "cosmic coincidence" problem [7]. An alternative proposal for dark energy is the dynamical dark energy scenario. This dynamical proposal is often realized by some scalar field mechanism which suggests that the specific energy form with negative pressure is provided by a scalar field evolving down a proper potential. Primary scalar field candidate for dark energy was quintessence scenario [8, 9], a fluid with the parameter of the equation of state lying in the range, $-1 < \omega < \frac{-1}{3}$. The analysis of the properties of dark energy from recent observations mildly favor models with w crossing -1 in the near past.

Meanwhile for the phantom model[10] of dark energy which has the opposite sign of the kinetic term compared with the quintessence in the Lagrangian, one always has $\omega \leq -1$. Neither the quintessence nor the phantom alone can fulfill the transition from $\omega > -1$ to $\omega < -1$ and vice versa. But one can show [11, 12, 13, 14] that considering the combination of quintessence and phantom in a joint model, the transition can be fulfilled. This model, dubbed quintom, can produce a better fit to the data than more familiar models with $w \geq -1$.

To realize a viable quintom scenario of dark energy it needs to introduce extra degree of freedom to the conventional theory with a single fluid or a single scalar field. The first model of quintom scenario of dark energy is given by Ref.[11] with two scalar fields. This model has been studied in detail later on [12, 13, 14] (to see the bouncing solution in the universe dominated by quintom matter refer to [15]). Recently there has been an upsurge in activity for constructing such model in string theory [16]. In the context of string theory, the tachyon field in the world volume theory of the open string stretched between a D-brane and an anti-D-brane or a non-BPS D-brane plays the role of scalar field in the quintom model [17]. The effective action used in the study of tachyon cosmology consists of the standard Einstein-Hilbert action and an effective action for the tachyon field on unstable D-brane or

D-brane anti D-brane system. What distinguishes the tachyon action from the standard Klein- Gordon form for scalar field is that the tachyon action is non-standard and is of the " Dirac-Born-Infeld " form [18]. The tachyon potential is derived from string theory itself and has to satisfy some definite properties to describe tachyon condensation and other requirements in string theory[19].

2 Reconstruction of non-minimally coupled tachyon gravity with extra term

We consider the action Ref.[19] for tachyon non-minimally coupled to gravity, then we add an extra term $T\Box T$ to the usual terms in the square root of this action. In that case the following action is the same as Ref.[20] just different to the $Rf(T)$,

$$S=\int d^4x\sqrt{-g}\left[\frac{M_P^2}{2}Rf(T)-AV(T)\sqrt{1-\alpha' g^{\mu\nu}\partial_\mu T\partial_\nu T+\beta' T\Box T}\right], \tag{1}$$

where $f(T)$ is a function of the tachyon T and corresponds to the non-minimal coupling factor. Here $V(T)$ is the tachyon potential which is bounded and reaching its minimum asymptotically. $M_P=\frac{1}{\sqrt{8\pi G}}$ is reduced Planck mass.
The action (1) can be brought to the simpler form to derive the equation of motion, energy density and pressure, by performing a conformal transformation as follows:

$$g_{\mu\nu}\longrightarrow f(T)g_{\mu\nu}. \tag{2}$$

The above conformal transformation yields to the following action:

$$S=\int d^4x\sqrt{-g}\left[\frac{M_P^2}{2}(R-\frac{3}{2}\frac{f'^2}{f^2}\partial_\mu T\partial^\mu T)\right.$$

$$\left.-A\tilde{V}(T)\sqrt{1-(\alpha' f(T)-2\beta' f'(T)T)\partial_\mu T\partial^\mu T+\beta' f(T)T\Box T}\right] \tag{3}$$

where $\tilde{V}(T)=\frac{V(T)}{f^2}$ is now the effective potential of the tachyon.
For a flat Friedman- Robertson- Walker (FRW) universe and a homogenous scalar field T, we have

$$\ddot{T}+3H\dot{T}=\frac{2\left[(\frac{ff''+\beta' f'}{f^2})T\dot{T}^2-2(\alpha'-2\beta'\frac{f'}{f}T)H\dot{T}\right]}{1+\frac{2\alpha'}{\beta'}-3\frac{f'}{f}T-\frac{3M_P^2}{2}(\frac{f'}{f})^2\frac{T}{\psi}}=\gamma, \tag{4}$$

where

$$\psi = \frac{\partial \mathcal{L}}{\partial \Box T} = -\frac{A\beta' \tilde{V} f T}{2h} \quad h = -\frac{A\beta' \tilde{V} f T}{2\psi} \tag{5}$$

also we have

$$h = \sqrt{1 - (\alpha' f - 2\beta' f' T)\partial_\mu T \partial^\mu T + \beta' f T \Box T}$$

and $H = \frac{\dot{a}}{a}$ is the Hubble parameter.
The energy momentum tensor $T^{\mu\nu}$ is given by the standard definition:

$$\delta_{g_{\mu\nu}} S = -\int d^4x \frac{\sqrt{-g}}{2} T^{\mu\nu} \delta g_{\mu\nu}.$$

So the energy density, and pressure are found to be

$$\rho = A\tilde{V}h + \frac{d}{a^3 dt}(a^3 \psi \dot{T}) + (\alpha' f - 2\beta' f' T)\frac{A\tilde{V}}{h}\dot{T}^2 - 2\dot{\psi}\dot{T} + \frac{3M_P^2}{4}(\frac{f'}{f}^2)\dot{T}^2, \tag{6}$$

$$p = -A\tilde{V}h - \frac{d}{a^3 dt}(a^3 \psi \dot{T}) + \frac{3M_P^2}{4}(\frac{f'}{f}^2)\dot{T}^2, \tag{7}$$

From equations (6) and (7) one can obtain the following expressions,

$$\rho + p = \frac{3M_P^2}{2}(\frac{f'}{f}^2)\dot{T}^2 + (\alpha' f - 2\beta' f' T)\frac{\tilde{V}A}{h}\dot{T}^2 - 2\dot{\psi}\dot{T}, \tag{8}$$

By substituting h from (5) into the Eqs.(8), (6)respectively we obtain

$$\rho + p = \frac{3M_P^2}{2}(\frac{f'}{f}^2)\dot{T}^2 - (\alpha' f - 2\beta' f' T)\frac{2\psi}{\beta' f T}\dot{T}^2 - 2\dot{\psi}\dot{T} = 2\hat{K}, \tag{9}$$

$$\rho = -(\alpha' f - 2\beta' f' T)\frac{2\psi}{\beta' f T}\dot{T}^2 - \dot{\psi}\dot{T} + \frac{3M_P^2}{4}(\frac{f'}{f}^2)\dot{T}^2 - \frac{A^2\beta' \tilde{V}^2 f T}{2\psi} + \psi\gamma = 2\hat{K} + 2\hat{V}, \tag{10}$$

where

$$\hat{V} = -\frac{A^2\beta' \tilde{V}^2 f T}{4\psi} + \frac{\psi\gamma}{2} + \frac{\dot{\psi}\dot{T}}{2} - \frac{3M_P^2}{8}(\frac{f'}{f}^2)\dot{T}^2 \tag{11}$$

Then we can write the Friedman equations as following

$$3M_p^2 H^2 = \rho_m + \rho = \rho_m + 2\hat{K} + 2\hat{V} \tag{12}$$

$$2M_p^2 \dot{H} = -\rho_m - \rho - P = -\rho_m - 2\hat{K} \tag{13}$$

Also we obtain following relation for equation of state

$$\omega = \frac{P}{\rho} = -1 + \frac{1}{1+\frac{\hat{V}}{\hat{K}}} \tag{14}$$

Using Eqs.(12), (13) we can write

$$\hat{K} = \frac{-\rho_m}{2} - M_p^2 \dot{H} \tag{15}$$

$$\hat{V} = \frac{3M_p^2 H^2}{2} + M_p^2 \dot{H} \tag{16}$$

As in present model, the dark energy fluid does not couple to the background fluid, the expression of the energy density of dust matter in respect of redshift z is [1]

$$\rho_m = 3M_p^2 H_0^2 \Omega_{m0}(1+z)^3 \tag{17}$$

where Ω_{m0} is the ratio density parameter of matter fluid and the subscript 0 indicates the present value of the corresponding quantity. Using the following relation

$$\frac{d}{dt} = -H(1+z)\frac{d}{dz}, \tag{18}$$

one can rewrite $\hat{K}$, $\hat{V}$ as following

$$\hat{K} = \frac{-3}{2} M_p^2 H_0^2 \Omega_{m0}(1+z)^3 + \frac{1}{2} M_p^2 H_0^2 (1+z) r' \tag{19}$$

$$\hat{V} = \frac{3}{2} M_p^2 H_0^2 r - \frac{1}{2} M_p^2 H_0^2 (1+z) r' \tag{20}$$

where

$$r = \frac{H^2}{H_0^2} \tag{21}$$

We obtain tachyon field in term of z from Eqs. (4), (11), (18) and (21) as,

$$\begin{aligned} & rH_0^2(1+z)^2 T'' - 2rH_0^2(1+z)T' + \frac{1}{2} r' H_0^2 (1+z)^2 T' \\ & - \frac{2\left[(\frac{ff''+\beta' f'}{f^2}) r H_0^2 (1+z)^2 T T'^2 + 2(\alpha' - 2\beta' \frac{f'}{f} T) r H_0^2 (1+z) T' \right]}{1 + \frac{2\alpha'}{\beta'} - 3\frac{f'}{f}T - \frac{3M_P^2}{2}(\frac{f'}{f})^2 \frac{T}{\psi}} = 0, \end{aligned} \tag{22}$$

The evolution Now using Eq.(11)we have

$$\tilde{V}^2 = \frac{4\psi}{A^2 \beta' f T}(\frac{\psi\gamma}{2} + \frac{1}{2} r H_0^2 (1+z)^2 \psi' T' - \frac{3M_P^2}{8} \frac{f'}{f}^2 r H_0^2 (1+z)^2 T'^2 - \hat{V}) \tag{23}$$

By using Eqs.(14), (19),(20) we obtain following expression for equation of state and sound speed

$$\omega(z) = \frac{P}{\rho} = \frac{(1+z)r' - 3r}{3r - 3\Omega_{m0}(1+z)^3} \tag{24}$$

$$c_s^2 = \frac{-2r' + (1+z)r''}{-9\Omega_{m0}(1+z)^2 + 3r'} \tag{25}$$

the sound speed is discussed for investigation of stability of the model and it necessary is to be $c_s^2 \geq 0$.
Then we obtain following equation for $r(z)$

$$r(z) = \Omega_{m0}(1+z)^3 + (1-\Omega_{m0})e^{3\int_0^z \frac{1+\omega(\tilde{z})}{1+\tilde{z}} d\tilde{z}} \tag{26}$$

Also by using Eqs.(16), (20), (21) we have following expression for deceleration parameter q

$$q(z) = -1 - \frac{\dot{H}}{H^2} = \frac{(1+z)r' - 2r}{2r} \tag{27}$$

3 Parametrization

Now we consider the three different forms of parametrization as following and compare them together.
Parametrization 1:
First Parametrization has proposed by Chevallier and Polarski [21]and Linder [22], where the EoS of dark energy in term of redshift z is given by,

$$\omega(z) = \omega_0 + \frac{\omega_a z}{1+z} \tag{28}$$

Parametrization 2:
Another the EoS in term of redshift z has proposed by Jassal, Bagla and Padmanabhan [23] as,

$$\omega(z) = \omega_0 + \frac{\omega_b z}{(1+z)^2} \tag{29}$$

Parametrization 3:
Third parametrization has proposed by Alam, Sahni and Starobinsky [24]. They take expression of r in term of z as followoing,

$$r(z) = \Omega_{m0}(1+z)^3 + A_0 + A_1(1+z) + A_2(1+z)^2 \tag{30}$$

By using the results of Refs.[25, 26, 27, 28], we get coefficients of parametrization 1 as $\Omega_{m0} =$

0.29, $\omega_0 = -1.07$ and $\omega_a = 0.85$, coefficients of parametrization 2 as $\Omega_{m0} = 0.28, \omega_0 = -1.37$ and $\omega_b = 3.39$ and coefficients of parametrization 3 as $\Omega_{m0} = 0.30, A_0 = 1, A_1 = -0.48$ and $A_2 = 0.25$.

The evolution of $\omega(z)$ and $q(z)$ are plotted in Fig. 1 and Fig. 2 respectively. Also, using Eqs.(19), (20) and the three parametrizations, the evolutions of $\hat{K}(z)$ and $\hat{V}(z)$ are shown in Fig. 3 and Fig. 4 respectively.

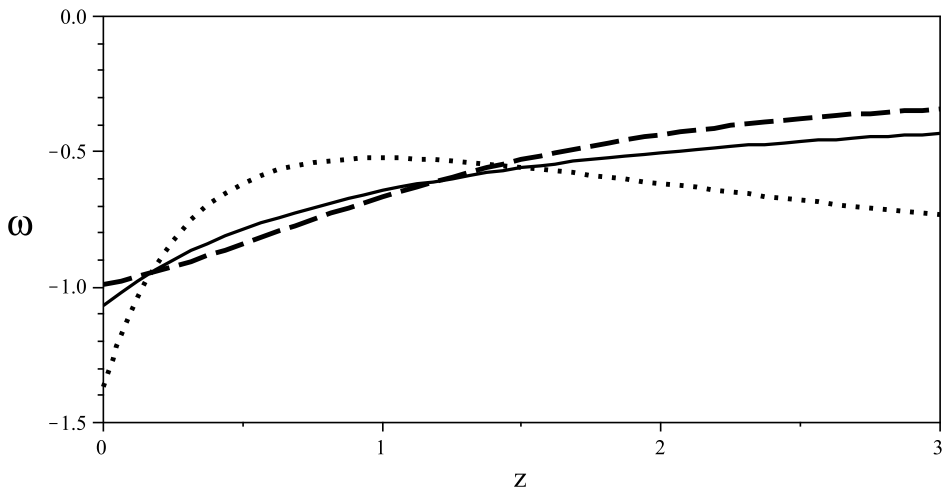

Figure 1: Graphs for the EoS parameter in respect of redshift z. The solid, dot and dash line represent parametrization 1, 2 and 3 respectively.

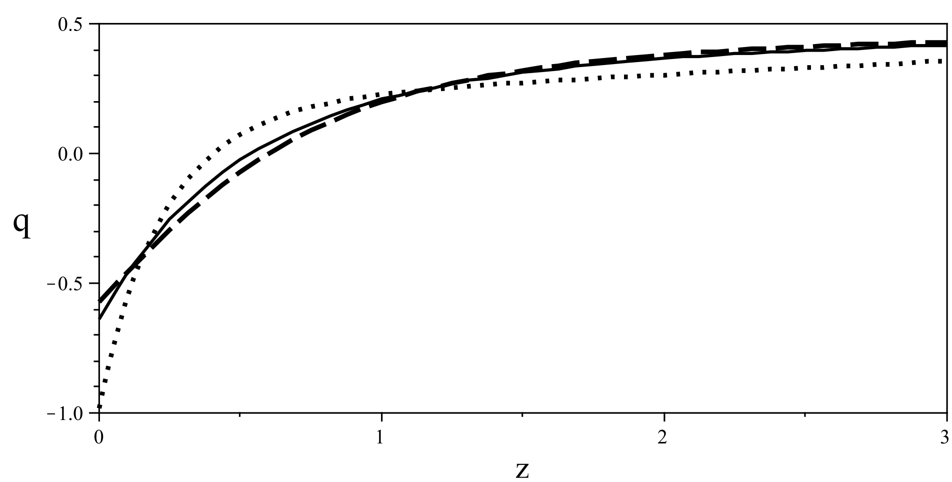

Figure 2: Graphs for the deceleration parameter in respect of redshift z. The solid, dot and dash line represent parametrization 1, 2 and 3 respectively.

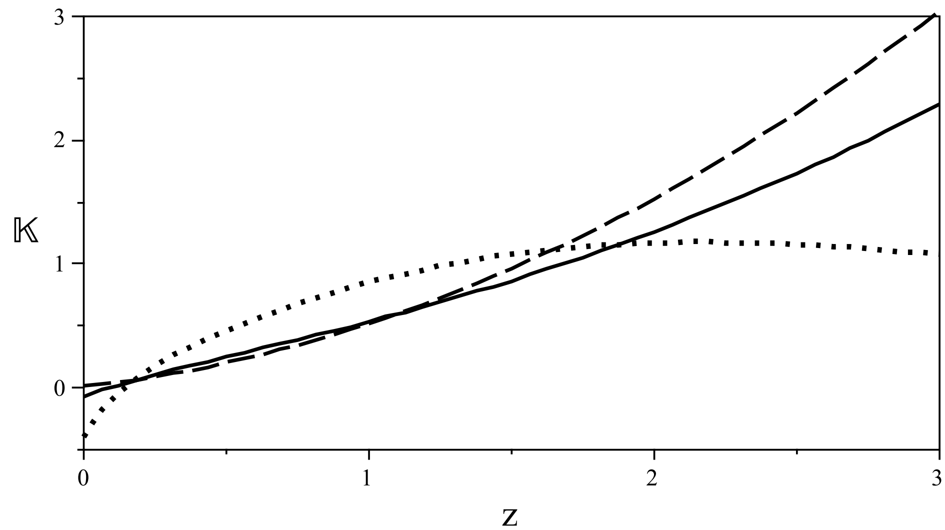

Figure 3: Graphs for the reconstructed $\hat{K}$ in respect of redshift z. The solid, dot and dash line represent parametrization 1, 2 and 3 respectively.

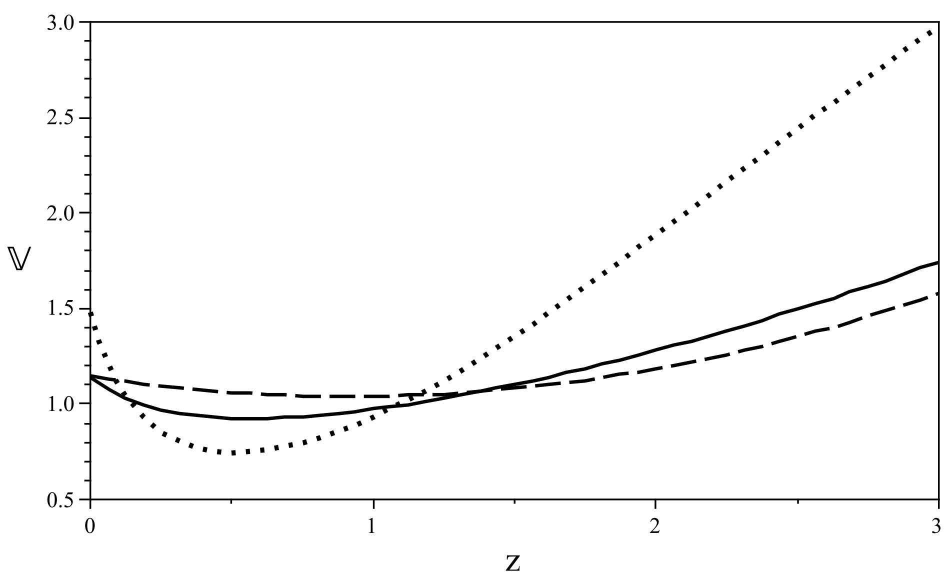

Figure 4: Graphs for the reconstructed $\hat{V}$ in respect of redshift z. The solid, dot and dash line represent parametrization 1, 2 and 3 respectively.

From Figs. (1),(2), (3) and (4), we can see parametrization 1 and 3 are same nearly and have slightly different from parametrization 2. EoS for parametrization 1 and 3 in Fig. (1) shows to tend nearly to -3, and for parametrization 2 tends nearly to -1. Acceleration for all of parametrization shows to tend to the positive value. The $\hat{K}$ and $\hat{V}$ increase for parametrization 1 and 3, parametrization 2 increase (decrease) for the $\hat{V}$ ($\hat{K}$).

By using Eq. (22), we can draw T with respective to the redshift by Runge-Kutta method in Fig. (5).

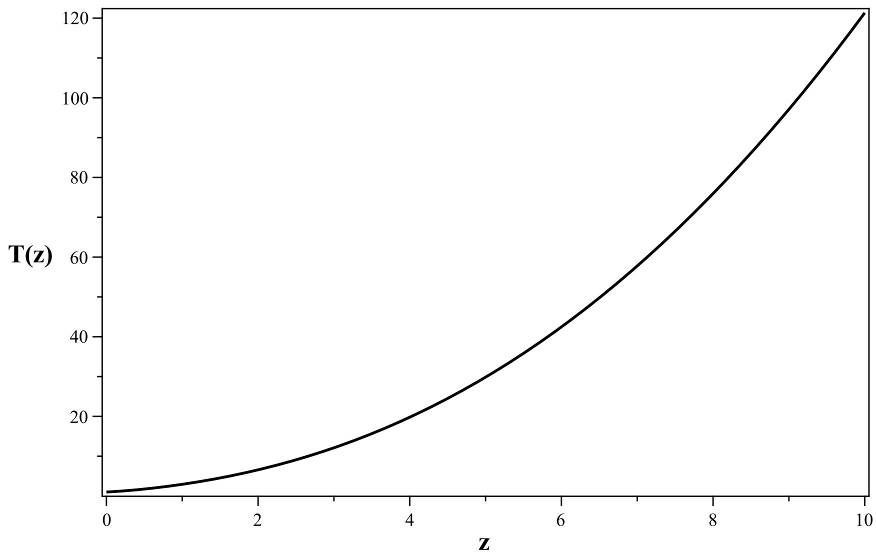

Figure 5: Graph for the evolution of the tachyon scalar field in respect of redshift z. It has calculated by numeric procedure of Runge-Kutta method.

The evolution of the tachyon scalar field with respect to redshift z are same for all parametrization 1, 2 and 3. Therefore all parametrization give us suitable results. Here we note that the second parametrization in addition to describe the dynamics of the tachyon scalar field is better than two others parametrization for satisfying the EoS, one can see this point in fig Fig. 1. Also slope of graph decrease in the early epoch.
Here, in order to discuss the stability of model we use Eq. (25), so we can obtain following condition,

$$r(z) \geq \Omega_{m0}(1+z)^3, \tag{31}$$

where is accurate for three above parametrization.

4 Conclusion

The quintom model of dark energy [11, 12, 13, 14] is of new models proposed to explain the new astrophysical data, due to transition from $\omega > -1$ to $\omega < -1$, i.e. transition from quintessence dominated universe to phantom dominated universe. In this paper, we have investigated a simple method for the reconstruction of the string-inspired quintom dark energy model with the action (3). This action is the same as Ref. [1] just different to the $Rf(T)$, where $f(T)$ is a function of the tachyon T and corresponds to the non-minimal coupling factor. Our aim was to see whether the non-minimal coupling can actually reproduce required values of cosmological observables, such as evolution of equation of state and the deceleration parameter in respect to the redshift z. Our result for effective kinetic

energy $\hat{K}$ is exactly the same as Ref. [1], but our result for effective potential energy $\hat{V}$, is different with [1]. However, our results for equation of state and the deceleration parameter in respect to the redshift z, are exactly similar to what have been obtained by the authors of [1]. Finally, we have reconstructed our model in the light of three forms of parametrization for dynamical dark energy. In Fig. 1 we have found that all the three forms of parametrization require a model that permits equation of state to cross cosmological constant boundary, $\omega = -1$, but the second parametrization in addition to describe the dynamics of the tachyon scalar field, it is better than two others parametrization for satisfying the EoS.

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